Combined Attitude Control of Small Satellite using One Flywheel and Magnetic Torquers

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***Abstract*- A combined attitude stabilization control method is proposed on the bases of using both flywheel and magnetic torquers in case of flywheel failures. Firstly, a combined control scheme is provided with control allocation loop, and the control allocation and magnetic unload algorithms are further developed. Considering a specified condition when only the pitch axis flywheel is available, a strategy is proposed to alter the reaction wheel to a momentum wheel while keeping the satellite stable from generated disturbances using magnetic torquers, then combined with three-axis magnetic torquers to stabilize satellite to nadir pointing. Numerical simulations demonstrate the proposed technique can dynamically achieve failure isolation system reconfiguration, and can also finish the high accuracy attitude control task of small satellite. It also prolongs life of space task. Another point is its excellent robustness, simple design, and real time calculation on-board.**

I. INTRODUCTION

Characteristics of "Better, Faster, and Cheaper" of micro satellite and its advantages such as maneuverability, rapid response, survivability, and excellent time and space coverage ability reflected in its application has made it increasingly popularized in many fields including communication, remote sensing, scientific research, planetary exploration, space-based defense, and education, which has made micro satellite become a necessary complement to large satellite. Because of the limitation in volume and weight for modern micro satellite, which often makes it impossible to equip the thruster system, reaction wheel has become most important actuator for attitude control of small-satellite. Examples that use reaction wheel in order to achieve high precision attitude control include Clementine [1], BIRD [2], and TS–1 of Harbin Institute of Technology [3].

Today, two strategies are often used to handle the attitude control problem resulted from flywheel failure. The first, conventional actuator redundant backup strategy, for example the common used 3+1 reaction wheel configuration, incorporating redundancy in the design enables the satellite to accomplish three-axis attitude control task even when a single reaction wheel fails to work. The second, more complicated controllers are used to achieve the control objectives with only two actuators, for example the time-invariant discontinuous control method proposed by Horri[4], and the attitude maneuver feedback control law based on area of a sphere using Riemannian Geometry proposed by Shimada[5].

However, the approach completely based on actuator redundant backup has its disadvantage, for example higher weight and more complicated mechanical system, and no longer satisfies the design goals of "Better, Faster, and Cheaper" of micro satellite. Because of the limitations of power, weight, size and cost, it's only practical to realize redundant backup for few key components for micro satellite attitude control system, so that it mainly depends on soft processing method in the mode of actuator failure to achieve the control objectives with remaining actuators. Wheel-based controller for under-actuated satellite can only accomplish large angle maneuver, while controllability of attitude stabilization is impossible with fewer than three devices. can not be achieved simultaneously. Thus exploring new attitude control strategies that is effective when flywheel failure happens has become an active area of research for micro satellite attitude control.

Magnetic torquers have mainly been used as secondary control actuator to assist other primary means of actuation for control and stabilization. Thus magnetic torquers have been used for momentum management of reaction wheels, damping augmentation in gravity gradient stabilized satellite, and attitude acquisition after orbit injection. Usually magnetic torquer does not work, its function has not been effectively used, therefore it is possible to use magnetic torquers combined with flywheel to accomplish the attitude control task while one or more flywheels fail to work.

Magnetic torquer and reaction wheel combined control strategy was proposed in some papers for one-axis reaction wheel failure[6]. When fault occurs on two flywheels, which means that there is only one flywheel that can work, there is no strategy for this kind of situation, because this situation is considered as low probability event, while this kind of fault is inevitable during practical working of flywheel. Take the FUSE satellite launched in June 1999 for example, the satellite suddenly stopped working on November 25th, 2001 because of the sharp increase of damping force on the yaw-axis reaction wheel. Same fault occurred again on the pitch axis reaction wheel on December 10th, 2001[7, 8].

This paper proposed a control strategy combined one wheel and magnetic torquers, control allocation and momentum magnetic unloading algorithm are also developed. Specially, a control strategy is proposed when the pitch flywheel is available, which suggests to spin-up the pitch axis reaction wheel so that it can function as a momentum wheel, so the axis of the momentum wheel is aligned to the orbit normal, favoring the pitch direction. The satellite pointing error in the pitch direction is controlled by the wheel speed, and the nutation of roll and yaw angular momentum is controlled by

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the magnetic torquers. Therefore, the pitch bias momentum method requires only one momentum wheel, and together with magnetic torquers, achieves three-axis control.

As mentioned above, the momentum wheel stabilizes attitude by producing angular momentum by spinning at a nominal speed, and controls pitch by controlling the speed. However, if the wheel is suddenly spun up from rest, the satellite attitude will become unstable due to exchange of angular momentum and torque. Because of this reason, momentum wheels must go through a start-up by slowly bringing up the wheel speed while keeping the satellite stable from generated disturbances using magnetic torquers. This paper proposes a new wheel start-up method, and studies performance validation and application range of such method through simulation.

II. Combined Control Scheme Using One Flywheel and Three-axis Magnetic Torquers

In this section, a control strategy combined with flywheel and magnetic torquers for micro satellite is proposed, as shown in Fig.1. The scheme works by adding a control allocation section between the controller and the actuator to achieve the allocation of the desired control command. Besides, the control system could adjust its allocation strategy dynamically according to fault information provided by the condition monitoring and fault diagnosis module to achieve system fault isolation and dynamic reconfiguration [9].

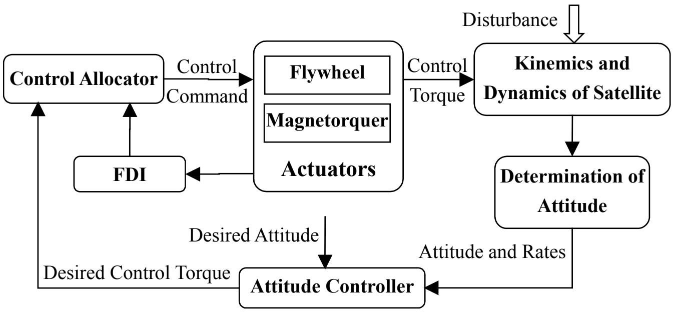

Fig.1 Combined control system structure with control allocator

It is possible to split the combined control design into the following two steps.

1. Design a control law specifying which total control effort to be produced.

2. Design a control allocator that maps the total control demand onto individual actuator settings.

There are more practical reasons to use a separate control allocation module. One benefit is that actuator constraints can be taken into account. If one actuator saturates, and fails to produce its nominal control effect, another actuator may be used to make up the difference. This way, the control capabilities of the actuator suite are fully exploited before the closed loop performance is degraded. Another benefit is that reconfiguration can be performed if the effectiveness of the actuators changes over time, or in the event of an actuator failure, without having to redesign the control law. A third major benefit is that the actuator utilization can be treated independently and can be optimized for the application considered. The actuator redundancy can be used for several purposes.

A. Control Law

According to the combined control structure with control allocator in last section, the control torques of the small satellite only depend on errors of the attitude and attitude rate, and what the actuator and how the allocation of control torque in different actuator no direct bearing on the controller. The attitude controller uses the simplest pd control law.

$$\boldsymbol{M}_c = \boldsymbol{\omega}_b \times \boldsymbol{I}\boldsymbol{\omega}_b - \boldsymbol{K}_p\boldsymbol{q}_e - \boldsymbol{K}_d\boldsymbol{\omega}_e - \boldsymbol{M}_d \tag{1}$$

where $\boldsymbol{I}$ is the inertia tensor, $\boldsymbol{\omega}_b$ represents the angular velocity of body-fixed reference frame with respect to an inertial reference frame given by $\boldsymbol{\omega}_b = [\omega_{bx} \quad \omega_{by} \quad \omega_{bz}]^{\mathrm{T}}$, the unit quaternion $\boldsymbol{Q}_e = \left[q_{e0} \quad \boldsymbol{q}_e^{\mathrm{T}}\right]^{\mathrm{T}}$ is error quaternion respect to reference attitude, $\boldsymbol{M}_c$ is control torque, $\boldsymbol{M}_d$ is disturbance torque, $\boldsymbol{K}_p, \boldsymbol{K}_d$ is respective derivative gain and proportional gain.

B. Control Allocator

In order to use three magnetic torquer and one flywheel for three-axis attitude control of small satellite simultaneously, the desired control torque is obtained by the sum of the control torques given by magnetic torquers (M_{cM}) and reaction wheel (M_{cW}), can be expressed as,

$$\boldsymbol{M}_d = \boldsymbol{M}_{cM} + \boldsymbol{M}_{cW} \tag{2}$$

The most simple direct allocation strategy, that is control torque of flywheel fault-axis is provided by magnetic torquers, and the other axis provided by the flywheel. Assumptions x-axis and z-axis reaction flywheel failure, then Eq. (2) projected along the x-axis and z-axis of body-fixed frames:

$$\begin{aligned} M_{cMx} &= M_{dx} \\ M_{cMz} &= M_{dz} \end{aligned} \tag{3}$$

Eq. (3) states that the magnetic torquers must provide a control torque whose x-axis and z-axis component is equal to the corresponding component of the required control torque vector. Since, in general, the magnetic torque vector has non-zero components also along y-axis, in order to meet condition (2), the remaining flywheel must balance the control torque surplus, with respect to the required one, given by y-axis component of the magnetic torque vector. Therefore, it results that:

$$M_{cWy} = M_{dy} - M_{cMy} \tag{4}$$

The magnetic control torque vector is given by the interaction of the magnetic dipole of the magnetic torquers with the Earth's magnetic field vector according to the following equations:

$$\boldsymbol{m} = \boldsymbol{B} \times \boldsymbol{M}_{cM} / \left|\boldsymbol{B}\right|^2 \tag{5}$$

It is possible to evaluate the magnetic control torque vector as follows:

$$\tilde{\boldsymbol{M}}_{cM} = \boldsymbol{m} \times \boldsymbol{B} \tag{6}$$

where $\boldsymbol{m}$ is the magnetic dipole moment, $\boldsymbol{B}$ is the earth magnetic vector using IGRF (International Geomagnetic Reference Field) 2000 model.

The maximum value of the elements $\boldsymbol{m}$ named as m_m, the ratio μ of rating dipole value to it can be calculated as:

$$\mu = \begin{cases} m_e/m_m, & m_e/m_m < 1 \\ 1, & m_e/m_m >= 1 \end{cases} \tag{7}$$

where m_e is the rating dipole value of the satellite. Multiplying magnetic control torque vector $\tilde{\boldsymbol{M}}_{cM}$ by the ratio value, we can obtain the magnetic control torque vector that satisfies the constraint of magnetic dipole.

The control torque of the reaction wheel is limited by:

$$M_{cWi} = \begin{cases} M_{cWi}(M_{\max}/\max(|M_{cWi}|)), & \max(|M_{cWi}|)/M_{\max} > 1 \\ M_{cWi}, & \max(|M_{cWi}|)/M_{\max} < 1 \end{cases} \tag{8}$$

where $M_{\max}$ is the maximum torque of reaction wheels.

C. Flywheel Magnetic Momentum Unloading Algorithm

Flywheel will absorb non-cycle disturbance torque and angular momentum from their nominal value, and ultimately achieving the rated speed and saturation. Magnetic momentum unloading is the use of the magnetic torque, interaction between the geomagnetic field and the magnetic dipole moment generated within the satellite, in order to unload excess momentum, to keep it in the vicinity of nominal value. This technique has been widely used for long-life satellites because it is relatively light-weight, it presents a low power consumption and is extremely inexpensive compare to other methods of control.

The differences between the wheel momentums and their nominal values can be written as $\Delta\boldsymbol{H}_w$, The simplest momentum unloading strategy is embodied in the cross product unloading law, as follows:

$$\boldsymbol{m}_u = -\frac{K}{\|\boldsymbol{B}\|^2}\boldsymbol{B} \times \Delta\boldsymbol{H}_w \tag{9}$$

where K is the unloading control gain.

Accordingly, the control torque given by Eq. (9) is

$$\boldsymbol{M}_u = \boldsymbol{m}_u \times \boldsymbol{B} \tag{10}$$

When $\Delta\boldsymbol{H}_w$ is perpendicular to $\boldsymbol{B}$, Eq. (10) can be written as $\boldsymbol{M}_u = -K\Delta\boldsymbol{H}_w$. This shows that the magnetic torque is always to reduce the excess momentum to achieve the objective of unloading. When $\Delta\boldsymbol{H}_w$ is not perpendicular to $\boldsymbol{B}$, $\boldsymbol{B}$ can be decomposed into $\boldsymbol{B}_{\Delta H}$, which is perpendicular to $\Delta\boldsymbol{H}_w$, and $\boldsymbol{B}_N$ that parallels to $\Delta\boldsymbol{H}_w$. Then the unloading magnetic torque can be written as:

$$\boldsymbol{M}_{uc} = -\frac{K}{\|\boldsymbol{B}\|^2}\left\{\|\boldsymbol{B}\|^2 - \left(\boldsymbol{B}\cdot\frac{\boldsymbol{A}_W\Delta\boldsymbol{H}_w}{\|\boldsymbol{A}_W\Delta\boldsymbol{H}_w\|}\right)\boldsymbol{B}_{\Delta H_w}\right\}\boldsymbol{A}_W\Delta\boldsymbol{H}_w \tag{11}$$

As $\|\boldsymbol{B}\|^2 \geq \left(\boldsymbol{B}\cdot\boldsymbol{A}_W\Delta\boldsymbol{H}_w / \|\boldsymbol{A}_W\Delta\boldsymbol{H}_w\|\right)\boldsymbol{B}_{\Delta H_w}$, the excess momentum will eventually be unloaded.

In order to limit the negative part of magnetic torque, generally, only when $|\boldsymbol{b}\cdot\Delta\boldsymbol{h}| < \varepsilon$, magnetic torquers start work to unloading, $\boldsymbol{b}$ and $\Delta\boldsymbol{h}$ are respectively unit direction vector of $\boldsymbol{B}$ and $\Delta\boldsymbol{H}_w$.

Each of the three magnetic torquers has its maximum dipole moment, and the direct addition of the desired control and unloading dipole commands can exceed this saturation value. In this case, the final dipole moment vector has a different direction than desired, and optimal x-axis and z-axis torque will not be realized. To prevent this, control dipole is decoupled from and prioritized over the unloading dipole by adding a linear combination of unload-only and control-only dipoles by use of Eq. (12),

$$\boldsymbol{m}_{MTB} = \boldsymbol{m} + k\boldsymbol{m}_u \tag{12}$$

Where, $\boldsymbol{m}_{MTB}$ is the final dipole moment command that is to be realized by the magnetic torquers, $0 \leq k \leq 1$ is a factor gain, defined as follows:

$$k = \frac{m_e - \max(m_i)}{m_e} \qquad i = x, y, z \tag{13}$$

In Eq. (12), a saturated $\boldsymbol{m}$ guarantees that k=0, in which case there will be no momentum unloading. If this condition exists long enough, the flywheel momentum will grow unacceptably high. When fine pointing control was not required, it is appropriate to reduce the control torque to increase the unloading torque.

III. Combined Control Method using Pitch-Axis Wheel and Three-axis Magnetic Torquers

This section gives a control strategy entailing one pitch wheel and three-axis magnetic torquers to achieve a relatively high control performance.

Combined attitude control using one-axis reaction wheel and three-axis magnetic torquers can only achieve a relatively low performance (More details discussed in the section of Mathematical Simulation), which makes it impossible to satisfy the high attitude control precision requirement.

For a special condition, when yaw and roll flywheel failure, pitch flywheel can work normally, it is a reasonable strategy to start-up the pitch flywheel to a momentum wheel, then combining with three-axis magnetic torquers to perform satellite attitude stabilization control in order to improve control precision of the system.

If the flywheel is spin up at a low rate suddenly, the satellite attitude stabilization will be disturbed because of the reaction torque. Traditional momentum wheel spinning up depends on thrusters or large gravity gradient torques. However, these methods are not effective under the circumstance discussed in this paper when fault occurs on a three-axis stabilized satellite without thruster system.

When reaction wheel failure, to ensure power safety and requirement of satellite telemetry and command, the attitude control accuracy can be lower, but not out of control. In such a request, an effective momentum wheel start-up method is proposed for small satellite equipped with flywheel and magnetic torquers. The basic idea is to realize three-axis stabilization for the micro satellite using reaction wheel and magnetic torquers firstly, which could be accomplished using the control scheme given in the section 2; and then to set a desired angular momentum, then to accomplish the wheel start-up using the magnetic unloading algorithm discussed in section 2.3, while ensuring attitude stabilization.

Use of the propose control scheme can make use of common control algorithm, without the need to design special control algorithms, so the implementation process relatively simple, and the satellites without change on the attitude control software code, to some extent, improve the reliability of satellite on orbit.

IV. SIMULATION RESULTS

A. Initial Conditions of Simulation

Numerical simulations are performed to validate the performance of the proposed algorithm for small satellite. The main parameters of simulation are as follows:

The orbit eccentricity is e = 0°, inclination is i = 97.7°, altitude is h=600km, and the argument of perigee is 120°.

The inertia matrix of the satellite is

$$\boldsymbol{I} = \begin{bmatrix} 19.05 & 0.23 & -0.72 \\ 0.23 & 20.0 & -4.09 \\ -0.72 & -4.09 & 21.76 \end{bmatrix} \mathrm{kg \cdot m^2}$$

Initial attitude are $\varphi = -2°,\ \theta = 2°,\ \psi = 2°$, and the initial attitude angular velocity is $\boldsymbol{\omega}(t_0) = [0.01, -0.07, 0.01]^{\mathrm{T}}\,°/\mathrm{s}$.

The maximum momentum of the reaction wheel is 0.2N.ms, the maximum torque is 0.03 Nm, static friction torque is 0.002N.m, and the inertia is $6.37\times10^{-4}\mathrm{kg\cdot m^2}$. The magnetic dipole is 35Am^2. And the 3-order IGRF (International Geomagnetic Reference Field) 2000 model is used.

Disturbance torques is modeled as follows:

$$M_{dx} = A_0(3\cos\omega_0 t + 1)\ ,$$

$$M_{dy} = A_0(1.5\sin\omega_0 t + 3\cos\omega_0 t)\ ,$$

$$M_{dz} = A_0(3\sin\omega_0 t + 1)$$

where $A_0 = 1.5\times10^{-5}\mathrm{N\cdot m}$.

B. Simulation Results and Analyze

According to the condition mentioned above, the simulations of combined attitude control scheme based on both flywheel and magnetic torquers are given, and the results are as shown in Fig.2-5.

Using the simulation parameters as above, attitude control results after flywheel started-up are shown in Fig.10-13.

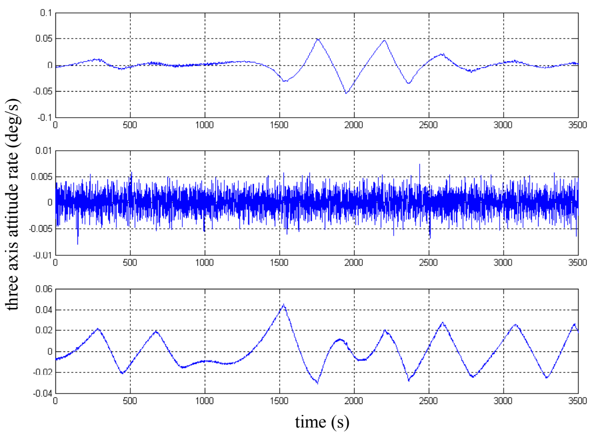

Fig.2 Attitude rate of three axes

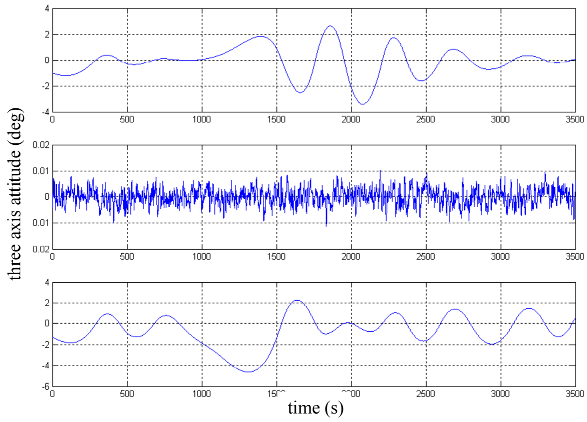

Fig.3 Attitude angle of three axes

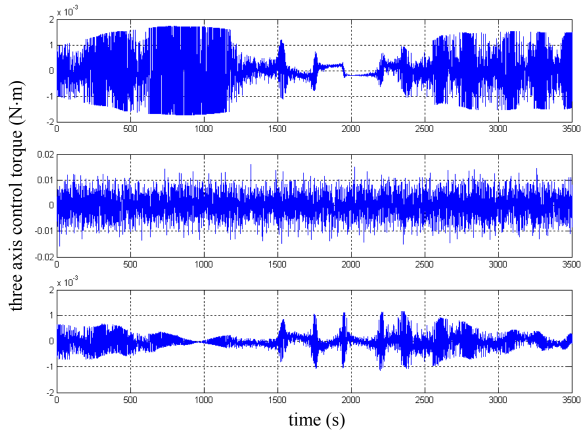

Fig.4 Control torque of three axes

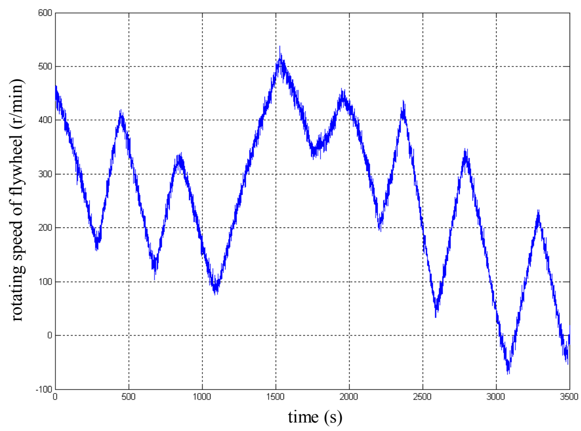

Fig.5 Rotating speed of flywheel

From the figures above, we know that, the combined control strategy using a one reaction wheel and magnetic torquers can stabilize satellite finally, with an error of 4 deg to attitude and 0.05 deg/s to attitude rate, it can't reach the purpose of high accuracy attitude control.

Following the start-up strategy based on magnetic torquers, the pitch axis flywheel starts-up from 0 r/min (with angular momentum of 0Nms) to 1500 r/min (with angular momentum of 0.2Nms), Fig.6-9 depict the process of flywheel starting-up.

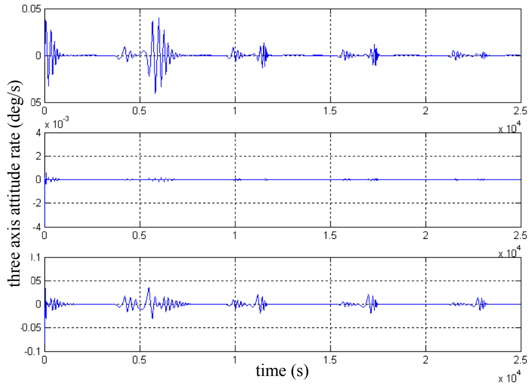

Fig.6 Attitude rate of three axes

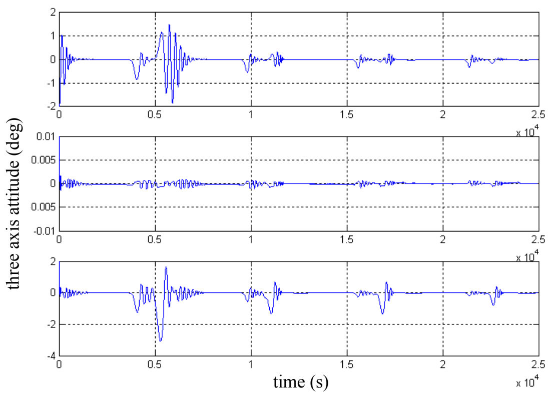

Fig.7 Attitude angle of three axes

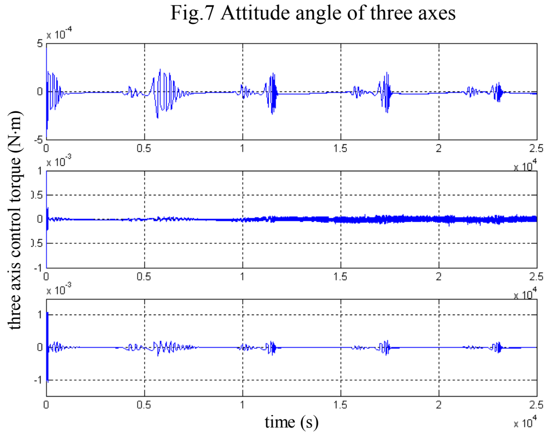

Fig.8 Control torque of three axes

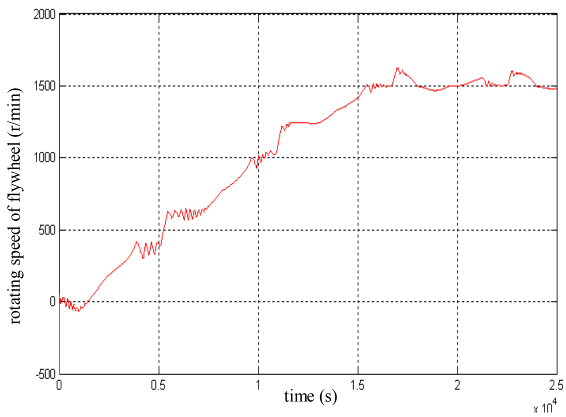

Fig.9 Rotating speed of flywheel

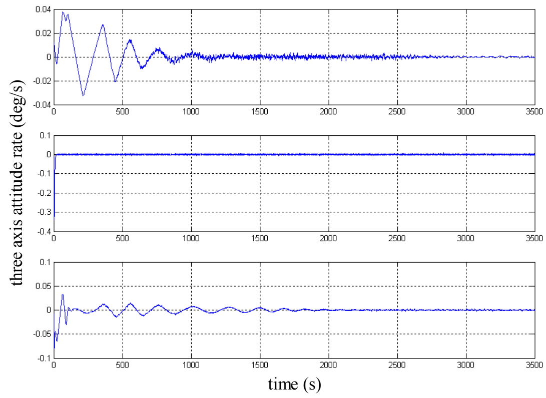

Fig.10 Attitude rate of three axes

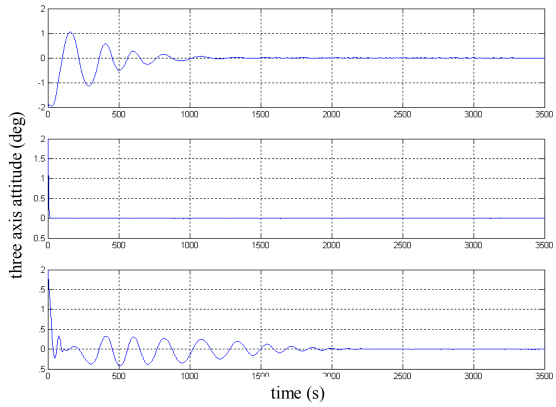

Fig.11 Attitude angle of three axes

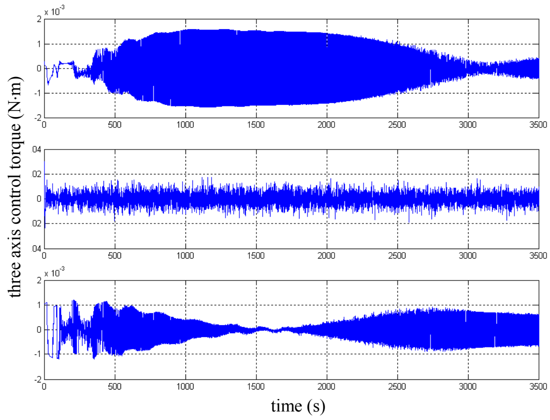

Fig.12 Control torque of three axes

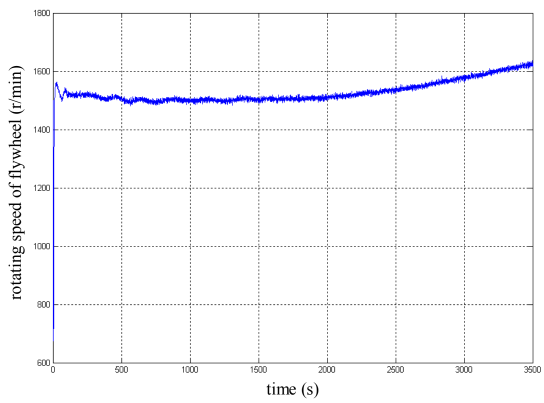

Fig.13 Rotating speed of flywheel

Compared to Fig.2-5, which represent the effect of control strategy using single flywheel and three-axis magnetic torquers, from Fig.10-13, the control effect is greatly improved. The attitude accuracy is about 0.05 deg, and attitude rate accuracy is about 0.003 deg/s, and matches high accuracy requirements of attitude control. The proposed strategy is confirmed to be feasible and effective.

V. Conclusions

In this paper, we considered the attitude control problem for small satellite equipped with reaction wheels and magnetic torquers. For the conditions that only one axis flywheel works, a combined attitude stabilization control method is proposed based on the combination of flywheel and magnetic torquers. A control strategy is proposed especially when the pitch axis flywheel is available, in which we spin-up the pitch axis reaction wheel to work as a momentum wheel. This paper also proposes a new wheel start-up method, the performance and application of this method is validated through simulation. The simulation results show the effectiveness and reliability of the proposed method, and provide theoretical basis for small satellites in-orbit failure treatment. At the same time the control methods can also be a primary control strategy for micro-satellite to reduce the number of actuators, the weight and costs.

Acknowledgment

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